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Internet of Things (IoT) is one of the common computing concepts used these days. It is everything that connects to the internet i.e. objects like cars, light bulbs, doors, etc. are connected to the internet via an embedded device such as a microcontroller. Wireless Sensor networks based on standards like ZigBee are popular as they require less power for operation and the cost of installation of the network is low.

This project was done to study the effect of different operating environments in which the network is installed and the signal strength of the antenna in both coordinator and the end device of the network using a DIGI XBEE3 ZIGBEE MESH KIT. The XBee modules were configured using the XCTU application as a coordinator, router, and end device. The tests were conducted in an indoor and outdoor environment using the radio range test tool in the XCTU application to study the signal strength of the receiver for both the Coordinator and end device.

The signal strength of ZigBee devices is affected by the environment in which they operate. So, to avoid the data loss the network should be free of obstacles and have a clear LOS. The selection and positioning of an antenna are an important factor in setting up the wireless network. A physical survey of the site where the network is to be installed can be done to visualize the wireless network coverage, figure out possible obstacles and interferences. The signal strength of the receiver from Range tests can be compared with theoretical calculations of the signal strength. Mesh networks can be done to prevent data loss and weakening of the signal as there will be multiple routes for the signal to travel.

Keywords	IOT, XBee, ZigBee, Fresnel, sensitivity, sensor networks

Contents

List of Abbreviations

API	Application Programming Interface
BSIG	Bluetooth Special Interest Group
dBi	Decibel Isotropic
dBm	Decibel Milliwatts
FFD	Full Function Device
GHz	Giga Hertz
IEEE	Institute of Electrical and Electronics Engineer
Kbps	Kilo Bit per Second
LOS	Line of Sight
LR-WPANs	Low Rate- Wireless Personal Area Networks
MAC	Medium Access Control
MHz	Mega Hertz
OSI	Open System Interconnect
PAN	Personal Area Network
PAN ID	Personal Area Network Identifier
RF	Radio Frequency
RFD	Reduced Function Device
SH	Serial Number High
SL	Serial Number Low
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver-Transmitter
Wi-Fi	Wireless Fidelity

1 Introduction

Internet of Things (IoT) is one of the common computing concepts used these days. It is everything that connects to the internet i.e. objects like cars, light bulbs, doors, etc. are connected to the internet via an embedded device such as a microcontroller. It describes the network of objects that are embedded with sensors, software, and other technologies to connect and exchange data with others over the internet.

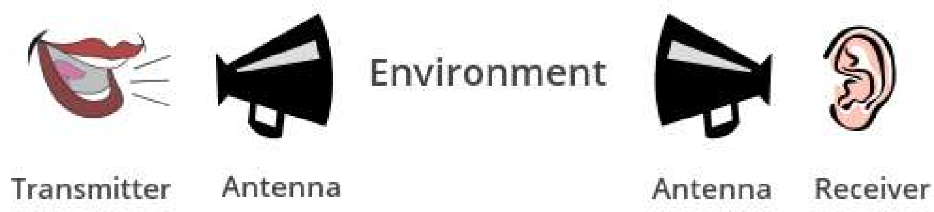

Figure 1: Communication. Copied from [1].

Communication involves transmitting and receiving whether it is a verbal one or between two radio modules. As shown in figure 1 various factors affect the communication between modules in a network such as environment in which communication is taking place, Antenna used in modules, and distance of the modules from sender to receiver. Visual LOS and RF LOS plays an important role to establish a long-distance wireless communication.

This project aimed to build a ZigBee mesh network consisting of a Coordinator, Router and End device using Digi XBee modules which are configured using XCTU software and the link sensitivity of the network was studied on different environments (both indoor and outdoor).

The project was conducted in two different phases:

- Configuration of XBee modules
- Measurement and Analysis

2 Radio Basics

2.1 Radio Waves

Radio waves are the type of electromagnetic waves which have a wavelength from 1millimeter to 30,000 meters and frequency from 10 Kilohertz to 300,000 Megahertz. They are mostly used in communication devices like television, mobile phones, radios, etc. When electric charges are accelerated, radio waves are radiated by them and transmitted by a radio transmitter and received by radio receiver through the antenna.

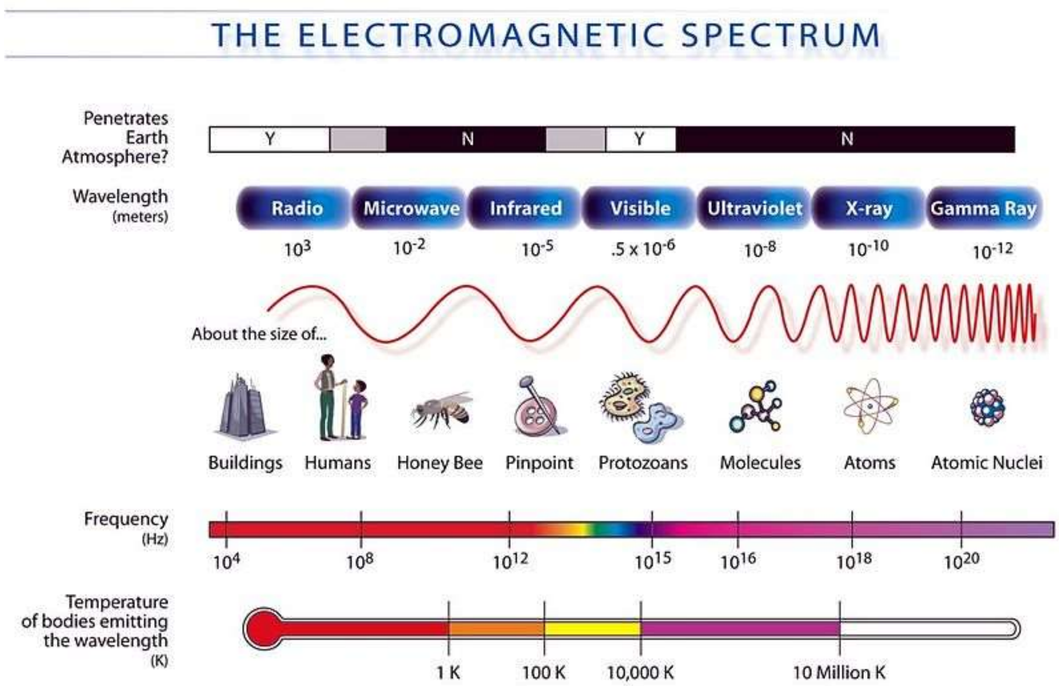

Figure 2: Electromagnetic Spectrum. Copied from [2]

Radio waves travel at the speed of light in a vacuum but in a material medium, their speed is slowed down by medium's permeability and permittivity and in Earth's atmosphere radio waves travel almost very close to the speed of light as air is thin. Radio waves are also capable of penetrating the earth's atmosphere as shown in figure 2.

2.2 Inverse Square Law

Radio waves unlike a wire communication requires lot of power as data through the wireless connections decay in an accelerated speed. This is because as the signal radiates away from the source, they start to spread rapidly like ripples in a water pool.

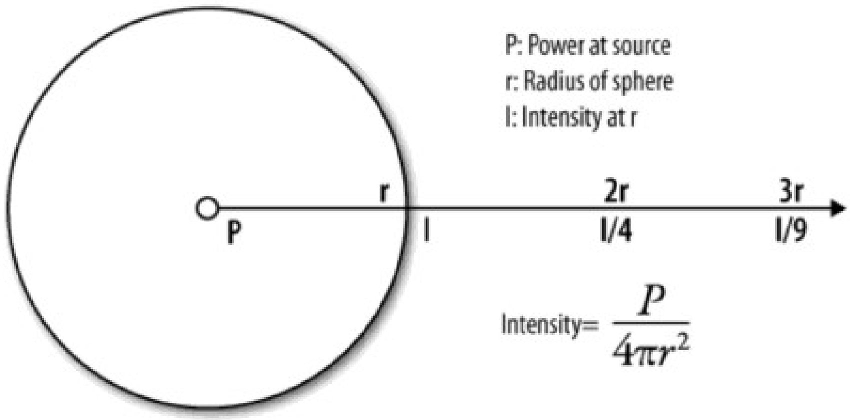

Figure 3: Inverse Square law. Copied from [3,25]

As shown in figure 3, based on inverse square law [3,25] the intensity of data transmission is affected by the distance the data covers. When the distance of the destination to send the data is doubled, the power consumption increases by four times. Since ZigBee devices are designed considering Inverse Square law, to reduce power consumption to send a data over long distance, data is sent over a short distance to its nearest neighbor and forwarded to the destination following this pattern. This is the reason behind low power consumption despite the longer distance data transmission.

2.3 Fresnel Zone

In a wireless communication to avoid a loss of signal, LOS between two wireless systems plays an important role. The wireless system needs to be free from any obstruction such as vegetation, buildings, wind farms, terrains, etc. that could obstruct LOS and interfere in communication.

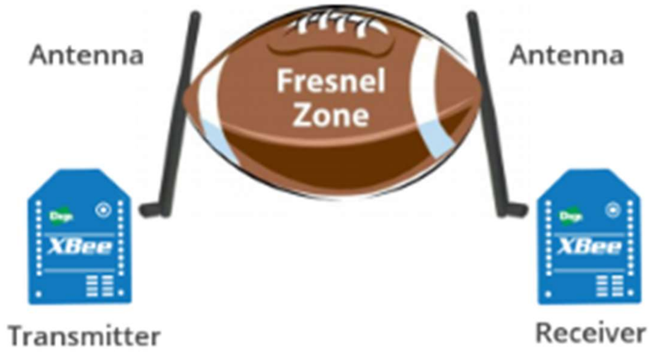

Figure 4: XBee Wireless Communication.Copied from [1]

The elliptical region between the transmitting antenna and the receiving antenna for wireless communication is the Fresnel Zone.The Fresnel Zone is named after French Civil Engineer and physicist Augustine-Jean Fresnel [4]. The frequency of operation and the distance between the transmitter and the receiver determines the size of the ellipse.

Fresnel Zone is based on the Huygens Fresnel principle which is an improvised work of Huygens principle

"*Every point on a wave-front may be considered a source of secondary spherical wavelets which spread out in the forward direction at the speed of light. The new wave-front is the tangential surface to all of these secondary wavelets.*"[5]

Christiaan Huygens was the first person to explain how wave theory can account for the laws of geometric optics.[5]

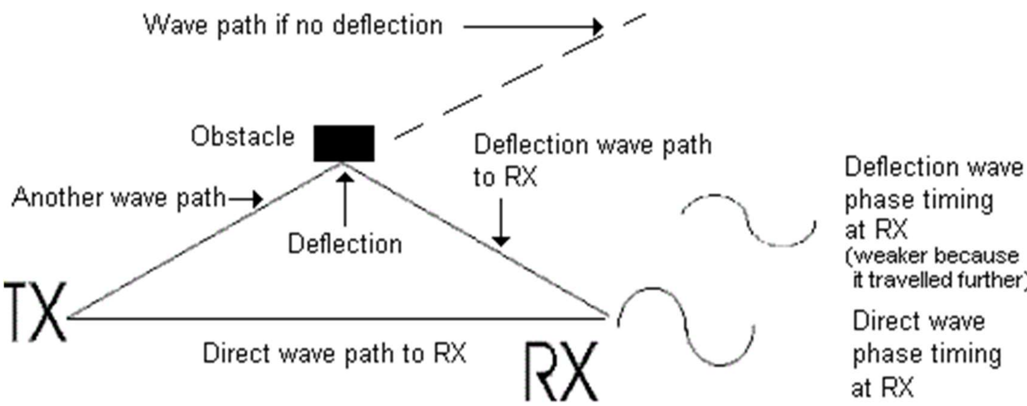

Figure 5: Radio waves transmission and deflection. Copied from [4]

Radio waves are transmitted in all directions by the antenna and in a circle if the antenna is Omni. The straight wave or the radio wave in radio LOS will be transmitted to receiver antenna. As shown in figure 5, other radio waves inside the signal might deflect to the receiving antenna and if the deflected waves are out of phase with the straight wave, the deflected waves have a phase canceling effect on the straight wave and will reduce the power of the arriving signal. The phase canceling effect's magnitude is the function of the signal strength and how out of phase is the deflected signal.

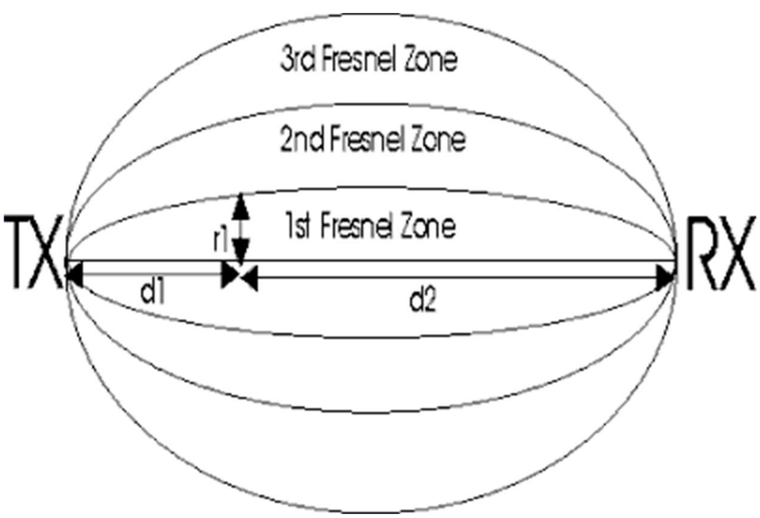

Figure 6: Fresnel Zones. Copied from [4]

The multiple deflections between transmitting antenna and receiving antenna are Fresnel Zones as in figure 6. Among these multiple Fresnel Zones, the first three Fresnel

Zones influence the in the wireless communication. First Fresnel zone being the strongest one will create 0º to 90º out of phase signals and so on. To maximize the receiving signal strength, the effect of out of phase signals should be minimized by ensuring the strongest signal is free of obstacle and does not deflect from its path. In general practice, antenna in transmitting and receiving ends are adjusted in such a way that 60% of the first Fresnel zone is clear [4].

3 ZigBee

3.1 Introduction of ZigBee

ZigBee is an open global standard by ZigBee Alliance based on which wireless technologies are developed for low cost, less power consumption, and IoT networks. It is based on IEEE 802.15.4 that describes the operation of LR-WPRANs. ZigBee devices can cover long distance for low data transmission with long battery life due to its mesh networking capability. ZigBee based networks are used in industries, home for remote operation of appliance, controlling lights, heating and cooling system control because of their low power consumption and reliable mesh network.
ZigBee being a set of layers built on top of 802.15.4 adds three important factors: Routing, Ad Hoc Network Creation, and Self-Healing Mesh. [3,26]

3.1.1 Routing

The process of selecting a path for communication in a network is Routing. Routing table define how one radio wave can pass through a series of other radio waves in wireless communication to the destination.

3.1.2 Ad Hoc Network Creation

A temporary network formed by the collection of wireless network hosts without the aid of any stand-alone infrastructure or centralized administration is Ad Hoc network. It is an automated process that creates an entire network of radios without any human intervention.

3.1.3 Self-Healing Mesh

This is a process of figuring out faults in the network i.e. if one or more radios are broken or missing from the network and reconfigure the broken one and try to find the alternate path for communication within the network.

3.2 Characterstics

- ZigBee devices operates in different frequency bands: 868 MHz, 915MHz and 2.4 GHz among which 2.4 GHz is the most common used frequency band.

- ZigBee devices have low speed data transmission rate with the maximum of 250 kbps.

- ZigBee devices are optimized for low duty cycle applications and less than 0.1% of total time for transmission.

- Range of the network of ZigBee devices is limited and depends upon the environment of the operation.

- In 2.4 GHz frequency, a ZigBee network operates over 16 channels while in 868 MHz and 915 MHz it operates over 11 channels.

- Maximum 255 nodes can be there in a ZigBee network which are asleep most of time for less consumption of energy.

3.3 Comparison of ZigBee with Bluetooth and Wi-Fi

Bluetooth and Wi-Fi both are wireless communication standards like ZigBee. ZigBee is based on IEEE 802.15.4 and Bluetooth is based on 802.15.1 and Wi-Fi is based on IEE802.11. Bluetooth is a standard by BSIG and Wi-Fi by Wi-Fi Alliance. Bluetooth is used to share data between fixed and mobile devices over short distances while Wi-Fi is capable of long-distance communication. The frequency in which Bluetooth operates is from 2.4GHz to 2.483 GHz while ZigBee can work in different frequencies and Wi-Fi in 2.4Ghz and 5Ghz. Bluetooth can communicate between devices with a range of 10 meters while ZigBee devices can communicate from 10 to 100 meters and even further through its mesh networking ability while Wi-Fi can communicate within 190 meters [6]. Wi-Fi is the most used wireless communication among these three standards and has a higher security risk in comparison to Bluetooth and ZigBee.

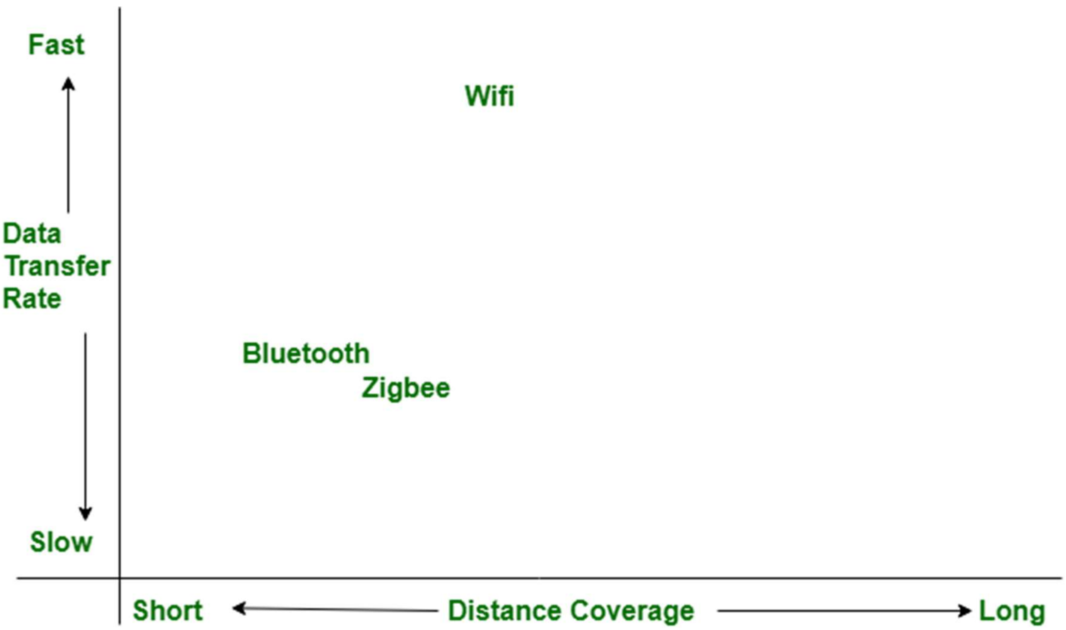

Figure 8. Comparison between ZigBee, Bluetooth and WI-FI. Copied from [7].

Wi-Fi is faster as well as capable of covering the longer distance for data transmission in comparison with ZigBee and Bluetooth as shown in figure 8. ZigBee devices consume less power in comparison to both Wi-Fi and Bluetooth and covering longer distance is possible by adding multiple routers within the network.

3.4 ZigBee Architecture

ZigBee network consists of four different layers as shown in figure 9. ZigBee wireless devices being capable to support both ZigBee and IEEE 802.15.4 standard. The protocol layers are based on the OSI basic reference model. Each layer in the protocol is responsible for a certain function within a network. This makes it easier to change the layer if needed. As the IEEE802.15.4 standard was independently developed than ZigBee standard, building a short-range network is possible without using the ZigBee standard layers for ZigBee wireless devices.

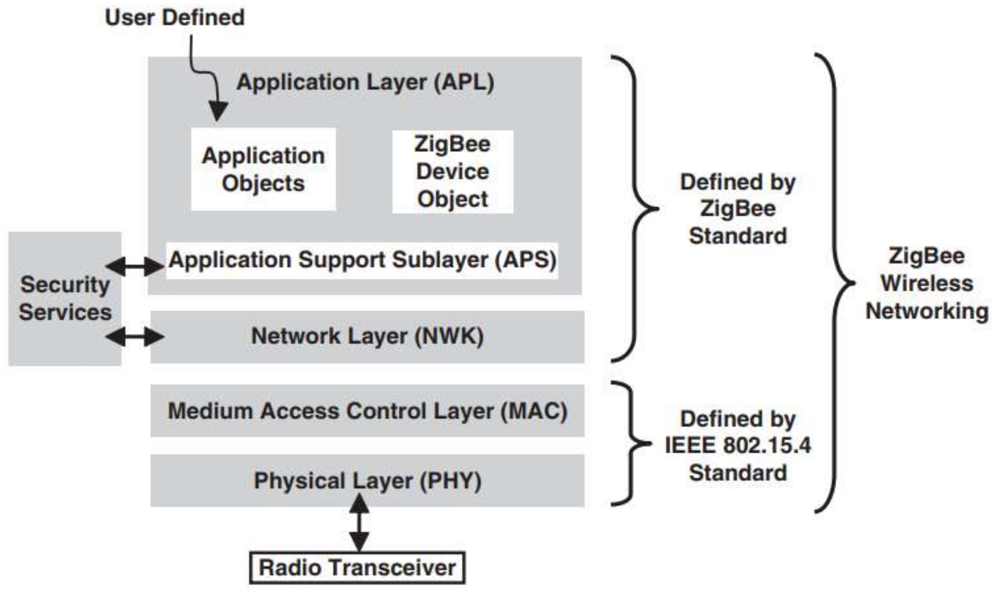

Figure 9. ZigBee Wireless Networking Protocol Layers. Copied from [8,5].

ZigBee Network Architecture can be classified into two different layers:

- Foundation layers
- Application and Interface layer

3.4.1 Foundation Layers

This layer is defined by the IEEE 802.15.4 standard and covers the MAC layer and Physical layer. The physical layer is responsible for describing how the devices are connected in a network. MAC layer manages RF data transmission with the devices in a network and has collision avoidance techniques.

3.4.2 Application and Interface Layer

This layer is defined by the ZigBee Standard. It covers the Application layer Network layer. The network layer acts as an interface between the MAC layer and application layer which is the reason that a ZigBee wireless device supports different network topologies such as Mesh topology, Star topology, and Tree topology.

The application layer defines objects like profiles, clusters, endpoints. The application layer has two sublayers Application Support sublayer and ZigBee Device object. Application Support sublayer filters data packets for end devices and checks redundancy as a ZigBee network supports retries during data transmission. The local and over the air management of the network is done by ZigBee Device Object.

3.5 Device Type

ZigBee wireless device consists of three different devices in a network based on IEEE 802.15.4 concepts of FFD and RFD devices. They are:

- Coordinator
- Router
- End Device

3.5.1 Coordinator

A Coordinator is an FFD device which is responsible for overall management of the network. In a ZigBee wireless network there must be a Coordinator to start the network and it selects the channel to be used for the network. It can permit other devices to join and leave network. In a ZigBee wireless network there is only one Coordinator.

3.5.2 Router

Router in a ZigBee Wireless network is an FFD device which is used to expand the network coverage. It finds the best route to transfer the message to the destination and is almost like Coordinator except the Router is not capable of starting the wireless network.

3.5.3 End Device

End device in a ZigBee Wireless is an RFD device which operates within the limited sets of IEEE 802.15.4 MAC layer. It consumes less power as it is capable of cyclic sleep which helps in reducing cost of the network. It connects to both Router and Coordinator and transfer applications packet.

3.6 ZigBee Network Topologies

Network topology is the arrangement of different devices in a network. Communication between these devices or nodes in the network can be both simplex and duplex.

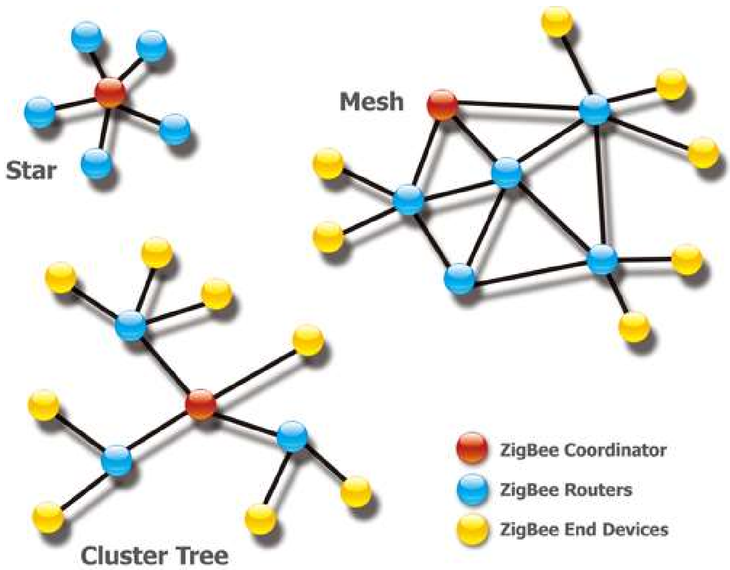

Figure 10. ZigBee topologies. Copied from [9]

As shown in figure 10, ZigBee wireless network can be done in following topologies:

- Star topology
- Cluster tree topology
- Mesh topology
- Tree topology

3.6.1 Star Topology

As shown in figure 10, the network is formed between a coordinator and multiple end devices in a star topology. Despite being simple and shorter routes for communication among nodes this topology depends on the coordinator for the communication and if the coordinator is gone, the network fails.

3.6.2 Cluster Tree Topology

As shown in figure 10, cluster tree topology is a tree topology in which a parent and its children are known as a Clusters. They are known by their Cluster ID. Cluster tree topology is supported by IEEE 802.15.4 rather than ZigBee.

3.6.3 Mesh Topology

Mesh topology as shown in figure 10 consists of a single Coordinator, multiple Routers, and End Devices. Data passes through multiple routes to reach its destination. In a mesh topology, the coverage of the network can be extended by adding more devices to the network as adding and removing devices is easier in a mesh topology. All devices can communicate to each other in the network and hence the data communication is complex in this topology compared to Star topology. This topology offers redundancy and is reliable for communication between devices in a wireless ZigBee communication.

3.6.4 Tree Topology

As shown in figure 11, tree topology consists of a central coordinator, multiple routers, and end devices.

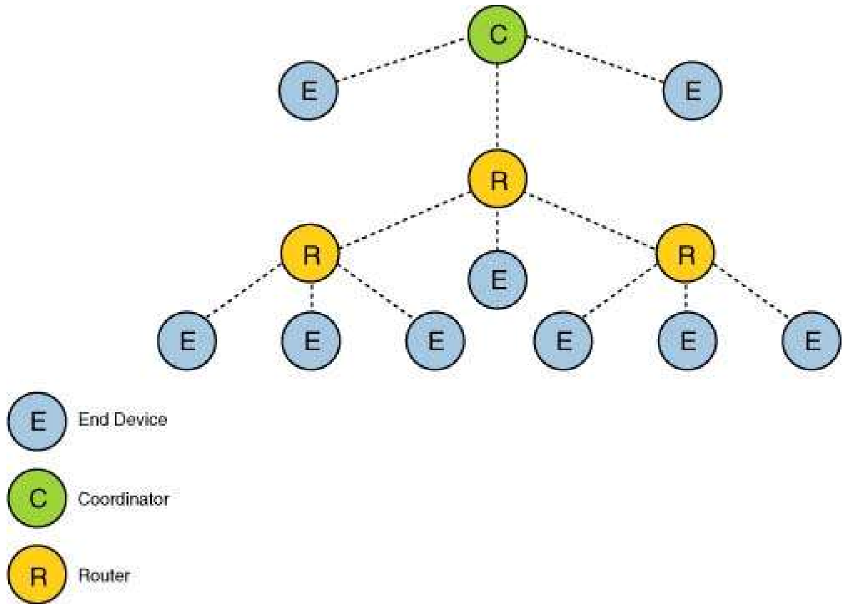

Figure 11. Tree Topology ZigBee. Copied from [10]

In a tree topology, router helps in extending the network coverage and can connects multiple end devices known as children. Coordinator and router being an FFD device can have child nodes. Child node can only communicate to its parent node i.e. either router or coordinator. So, if the parent node dies, the child node is out of network and despite the distance between two different nodes the communication is not possible in this topology.

4 XBee in General

XBee also known as Digi XBee is a RF module designed and manufactured by an American company Digi International. These modules are capable of wireless connection in a range of protocols and form factors (surface mount, micro-mount, and through hole) to be able to support less power consuming application. They are configurable via Digi XCTU configuration software. They are used in a large industry to monitor and control complex machines as well as at home for the daily use.

Figure 12: XBee Communication. Copied from [11]

As shown in figure 12, XBee module in a wireless network communicates in two different ways i.e. Serial Communication and Wireless Communication.

4.1 Serial Communication

Serial Communication in an XBee module is done through UART to connect it to different microcontrollers or also to the computer for configuration. It can transmit the data received from serial connection through wireless connection and vice versa. The figure 12 shows serial connection between XBee modules with microcontroller and a computer.

XBee modules supports two different operating modes i.e. Transparent mode and API mode which establishes the way the host device communicates with an XBee module for serial communication.

4.1.1 Transparent Mode

In this mode of communication, the data is displayed across all the nodes i.e. sent over the air as soon as the input from the serial mode is obtained exactly the way it is received. The communication in transparent mode has the same results as the wired connection.

Figure 13: XBee configuration in a transparent mode. Copied from [12].

As shown in figure 14, the communication mode in transparent mode is done between two modules by configuring the DH and DL parameters with SH and SL of the other XBee i.e. SH and SL of XBee A for DH and DL of XBee B and vice versa. Despite the operation in transparent mode is simple, the new destination address needs to be configured each time to communicate with a new device in the communication.

4.1.2 API Mode

API mode is the mode in which data are sent across the network in form of an organized packets and a determined order as shown in figure 14. The data sent in this mode is only accessible to the destination node and hence establishing a complex communication is possible between modules. To communicate in API mode, the device does not need to be configured by command mode and hence communication among multiple devices is easier unlike transparent mode. In API mode it is easier to identify the source of the data and if the data is sent successfully over the network or not. Also, it is possible to perform advanced network management and diagnosis.

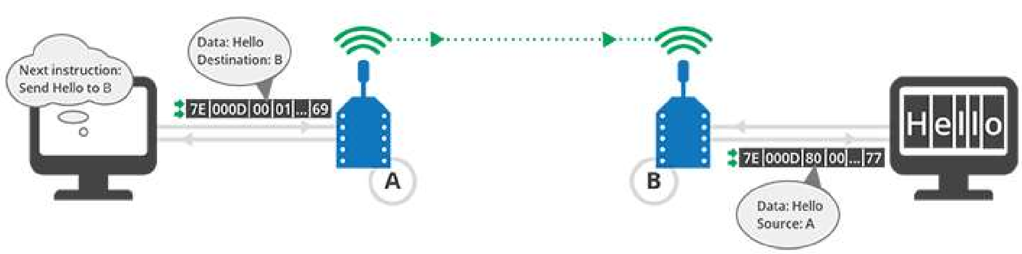

Figure 14: XBee API Mode Communication. Copied from [13].

4.1.2.1 API Frame Structure

Frames are the structured data packets in API mode. Frames along with the data from serial input over wireless communication contain extra information such as the signal quality, source, and destination of the data. This is the reason behind complex communication and the possibility to know if the data transmission was successful or not.

Start delimiter	Length		Frame data								Checksum
1	2	3	4	5	6	7	8	9	...	n	n+1
0x7E	MSB	LSB	API-specific structure								Single byte

Figure 15: XBee API frame structure. Copied from [14].

As in figure 17 an API frame consists of following structures. They are:

- Start delimiter: This is the first byte of the frame and indicated the beginning of the data frame and has a constant value of 0X7E.

- Length: It specifies the total number of bytes included in frame data. Start delimiter, length, and checksum is excluded by the two-byte value of length.

- Frame data: The frame data consists of frame type and data in the frame. Frame type varies between Sender and Receiver and indicated the information is organized in the data field.

- Checksum: It helps in testing data integrity and is the last byte of the frame.

4.1.2.2 Supported Frame Structure

Different types of frames are supported by XBee modules as shown in figure 16 and depend on the type of module being used. Some of the frame structure supported by XBee modules are:

API ID	Frame name	Description
0x08	AT Command	Queries or sets parameters on the local XBee
0x09	AT Command Queue Parameter Value	Queries or sets parameters on the local XBee without applying changes
0x10	Transmit Request	Transmits wireless data to the specified destination
0x11	Explicit Addressing Command Frame	Allows Zigbee application layer fields (endpoint and cluster ID) to be specified for a wireless data transmission
0x17	Remote AT Command Request	Queries or sets parameters on the specified remote XBee module
0x21	Create Source Route	Creates a source route in the module
0x24	Register Joining Device	Registers a module with the Trust Center

Receive data frames are received through the serial output, with data received wirelessly from remote XBees:

API ID	Frame name	Description
0x88	AT Command Response	Displays the response to previous AT command frame
0x8A	Modem Status	Displays event notifications such as reset, association, disassociation, and so on.
0x8B	Transmit Status	Indicates wireless data transmission success or failure
0x90	Receive Packet	Sends wirelessly received data out the serial interface (AO = 0)
0x91	Explicit Rx Indicator	Sends wirelessly received data out the serial interface when explicit mode is enabled (AO 0)
0x92	IO Data Sample Rx Indicator	Sends wirelessly received IO data out the serial interface
0x94	XBee Sensor Read Indicator	Sends wirelessly received sensor sample (from a Digi 1-wire sensor adapter) out the serial interface
0x95	Node Identification Indicator	Displays received node identification message when explicit mode is disabled (AO = 0)
0x97	Remote AT Command Response	Displays the response to previous remote AT command requests
0x98	Extended Modem Status	Displays what is happening during the association when Verbose Join is enabled (DC10)
0xA0	Over-the-Air Firmware Update Status	Provides a status indication of a firmware update transmission attempt
0xA1	Router Record Indicator	Displays the multiple route hopes after a Zigbee route record command
0xA3	Many-to-One Route Request Indicator	Indicates a many-to-one route request is received
0xA5	Join Notification Status	Indicates a module attempts to join, rejoin, or leave the network

Figure 16: Frame name and description. Copied from [15].

4.1.3 Comparison Between API and Transparent Mode

The transparent mode being a simple interface is used to broadcast messages across devices in a network while API mode is used when wireless data is sent to multiple destinations (devices). API mode has data in frame structure and hence contains the sender and receiver's address. API mode is much faster than transparent mode for wireless communication as there is no need to configure the device for every communication, unlike transparent mode. API mode has several advanced features such as advanced networking diagnostics and firmware upgrades. Data in API mode contains details of transmission such as sender and receiver's address, success or failure of the data transmission, and reasons for the success or failure of the transmission. Data in transparent mode are identical across the devices in a network while in API mode both the sent and received data are different as they are structured in the packet of a specific format.

4.2 Wireless Communication

Both XBee modules must be in a same network to transmit data from one XBee module to another. The key factors needed to manage network and transmit information between two XBee modules are:

- Addressing
- PAN Address
- Channels

4.2.1 Addressing

In a wireless connection of XBee modules, they have their address same as postal address or email address based on which an XBee is known.

Type	Example	Unique
64-bit	0013A20012345678	Always
16-bit	1234	Yes, but only within a network
Node identifier	Bob's module	Uniqueness not guaranteed

Figure 17: XBee addressing. Copied from [16].

As shown in figure 17, there are three types of XBee addressing in a Zigbee network which serves a purpose. They are:

- 64-bit address
- 16-bit address
- Node Identifier

4.2.1.1 64-bit Address

The 64-bit address also known as MAC address is an address used in XBee to distinguish it from other devices in the network and to prevent redundancy of the information within the network. It is guaranteed to be unique and is assigned to Digi by the IEEE. A 64-bit address can be found on the XBee modules and using the XCTU software by reading the SH and SL parameters which are stored in two 32-bit values. So, basically, a 64-bit address is the combination of SH and SL. For example, SH of an XBee module is 0013A200 which is standard for all XBee devices and SL is 418746CD, then its 64-bit address is 0013A200418746CD.

4.2.1.2 16-bit Address

When a device joins a ZigBee network, it is assigned a random 16-bit address which is also known as a network address. A 16-bit address can be read by using MY parameters on XCTU software. By default, 0000 is the address reserved for a coordinator in a network while FFFE is a value from the device which has not joined a PAN.

4.2.1.3 Node Identifier

The node identifier is the text which is user understandable i.e. it allows users to address the module and can be any name assigned by the user. The same node identifier can be assigned to different modules in the network hence uniqueness is not guaranteed.

4.2.2 PAN Address

ZigBee networks being a Personal Area Network has a unique PAN ID to define each network. PAN ID is a parameter setup by a coordinator on a network and ZigBee devices join the network when they discover the network, or they are preconfigured with PAN ID the same as the coordinator.

4.2.3 Channels

XBee modules must operate at the same frequency to be able to communicate with each other. XBee modules such as XBee S2C/S2D and XBee3 supports 16 channels defined in the 802.15.4 physical layer with some exceptions as:

- S2C/S2D parts have reduced maximum power (~3dBm) with channel 26.
- S2C XBee-PRO device supports 15 of the 16 channels and channel 26 is not supported by the S2C modules.
- Channel 26 is supported by XBee3-pro parts at a reduced maximum output power (~8dBm).

4.3 AT Mode

AT mode or command mode is used to talk to remote devices in the network without sending data. It can be used to configure remote XBee in a network or alter the way it behaves within the network. AT command '+++' is used in a transparent mode to switch a device into AT mode and if the user does not give any input within 10 seconds, the device automatically returns into the transparent mode from AT mode. In API mode, it is possible to configure remote XBee without entering AT mode. As shown in figure 16, API ID 0x08, 0x09, and 0x17 can be used to configure or change parameters of remote xbee in API mode.

Some basic AT commands are AT, ATCN and ATWR. AT command checks the connection with the module i.e. if the remove module is in network or not. ATCN command is used to exit this mode and if there is no input for 10 seconds the module exits this mode on its own. ATWR command is used to save the current configuration to non-volatile memory so the device loads the same parameter next time it is powered.

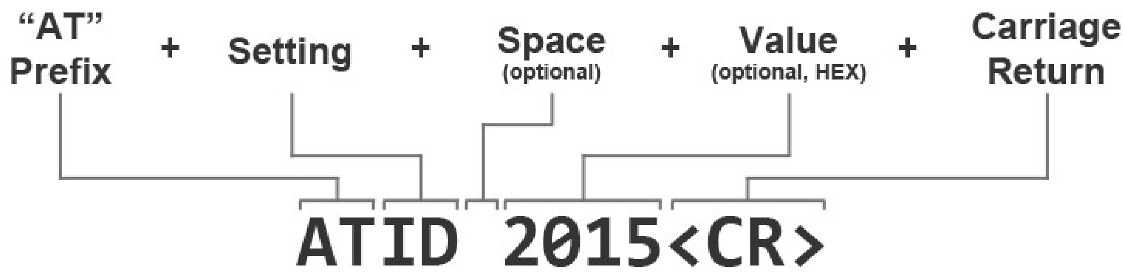

Figure 18: XBee AT code. Copied from [17].

The code in figure 18 is used to change the ID of the module to 2015 in AT mode.

5 Component and Application Used

5.1 Digi Mesh Kit

Digi mesh kit consists of three XBee 3 modules with surface mount (SMT) board along with an external antenna and Micro-USB cables to connect the SMT board to serial connector as shown in figure 19. The serial connection can both power up the device and connect the device to the PC for configuration.

Figure 19: Digi XBee 3 Mesh kit. Copied from [18].

The XBee 3 module is a 2.4GHz RF surface mount module with dimensions of 2.199 x 3.4 x 0.368cm. These modules have FCC/IC Test Transmit Power Output range approval of -6.8 to +8dbm. For microcontroller connection, XBee modules have wired communication interface of both UART and SPI with standard UART baud rates up to 921600 b/s and non-standard baud rates up to 967680 b/s with 5Mb/s burst speed for SPI communication. XBee modules have an outdoor range for clear RF LOS of about 1200 meters and an indoor range of about 60m [18]. In practical use, the range can be affected by the environment in which it is used, and obstacles and other wireless networks present.

5.2 XCTU

XCTU is a multi-platform compatible free application which is used to configure Digi RF modules via a graphical user interface. It includes all the tools needed by developers to configure and implement networks through the DIGI RF modules. In figure 20, the user interface of XCTU is shown and devices are discovered using discover devices function.

Using this application, the RF devices can be managed and configured over the network i.e. remote devices can be configured by the local coordinator.

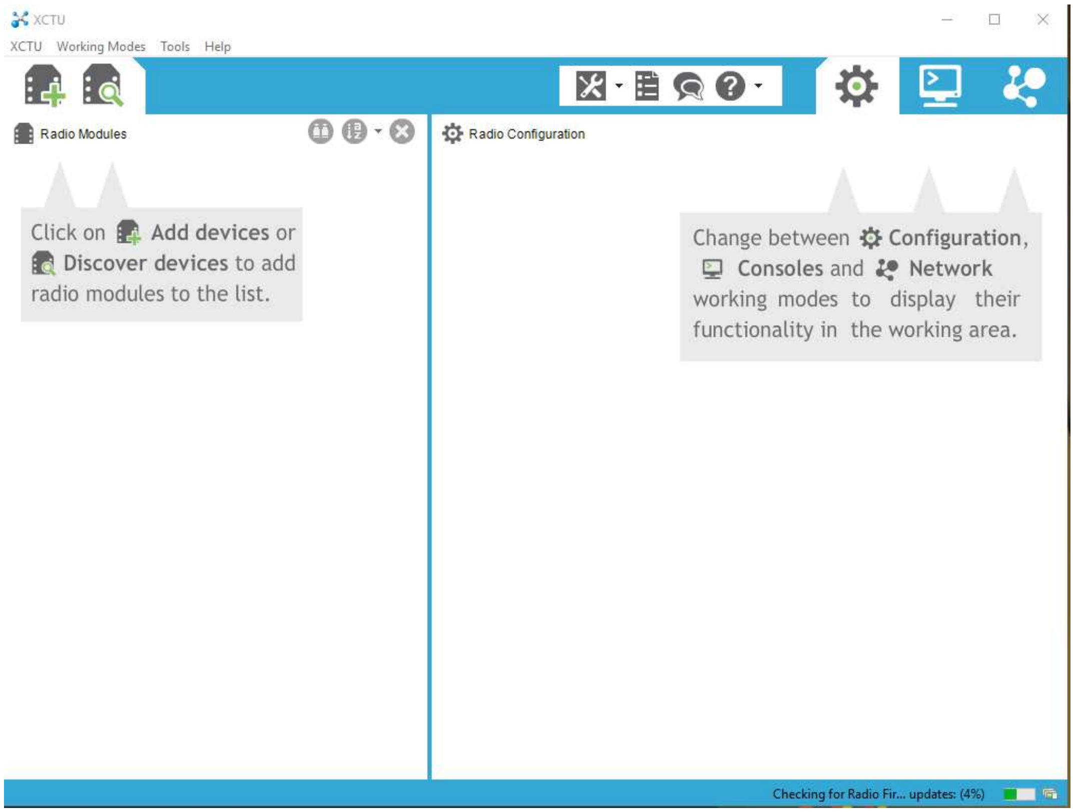

Figure 20: Screenshot from XCTU application.

6 Link Sensitivity Measurements

Received Signal Strength Indicator (RSSI) is a measurement of signal quality in a radio link. It is an estimated measure of power present in a radio signal received by the receiver antenna. It is measured in dBm which is a measurement for power level of received signal with one milliwatt as a reference power. It is used to define the signal strengths for radio and audio frequencies. Greater the dBm value, more power is present in the received signal when received by the antenna i.e. -10dBm RSSI is better signal quality than -50dBm RSSI.

To study the link sensitivity of ZigBee network, remote RSSI values of both the nodes (coordinator and end device) in the network can be crucial. RSSI is only an indication of RF energy at receiving end antennas port which can be affected by background noise and interference by other signals present in the environment such as Wi-Fi, Bluetooth, and Cellular network. The study based on RSSI might not be enough for the understanding on reliability of network to be established. Percentage of received data in the receiving end can be considered while setting up a network in to minimize the error.

The tests were conducted in two different environments (indoor and outdoor), configuring the XBee devices as coordinator, router, and end device by in API mode.

Param	XBee A	XBee B	XBee C	Effect
ID	2015	2015	2015	Defines the network that a radio will attach to. This must be the same for all radios in your network.
JV	—	Enabled [1]	Enabled [1]	Verifies if a coordinator exists on the same channel to join the network or to leave if it cannot be found.
CE	Enabled [1]	—	—	Sets the device as coordinator.
DH	—	0	0	Defines the destination address (high part) to transmit the data to.
DL	—	0	0	Defines the destination address (low part) to transmit the data to. The address 0000000000000000 can be used to address the coordinator.
NI	COORD	ROUTER	END_DEVICE	Defines the node identifier, a human-friendly name for the module. The default NI value is a blank space. Make sure to delete the space when you change the value.
SP	1F4	1F4	1F4	Defines the duration of time spent sleeping. 1F4 (hexadecimal) = 500 (decimal) x 10 ms = 5 seconds.
SM	—	—	Cyclic sleep [4]	Enables cyclic sleep mode in the end device.
SO	—	—	2	Keeps the module awake during the entire period.

Note The dash (—) in the table means to keep the default value. Do not change the default value.

Figure 21: XBee Configuration Parameters. Copied from [19]

After modifying the Parameters with the values as shown in figure 21 using the XCTU application, a mesh network of XBee modules is formed and nodes can be connected to coordinator and vice versa to perform a link test which can be done by using Range test in the XCTU tools menu.

Range test was conducted for both Coordinator and End device to check the similarity and accuracy of the obtained data. 100 packets of 50 bytes data were sent across both devices through the cluster ID 0x12 range test type. A unique 16-bit number to identify each cluster which is a set of attributes grouped together is Cluster Identifier (ID). Cluster ID is used by Xbee modules for all data transmission. On 0x12 as Cluster ID value, the receiving module echoes the transmitted packet back to the source device.

The time window for the test was one minute with 1000ms Rx and Tx interval. Both local and remote RSSI in dBm was obtained through the range test along with the received packets in the communication.

6.1 Indoor Tests

Indoor test was conducted in two different ways i.e. room to room in a same apartment and room to corridor in a same building. Limited space access and closure of the common areas resulted in conducting test on smaller distance up to 20m. Table 1,2, 3, and 4 from Appendix 1 contains the data obtained from the Indoor tests conducted using range test tool.

6.1.1 Room to Room

Tests were done by placing a fixed coordinator and changing the distance between coordinator and router facing different physical obstacles along with the presence of cellular network and WI-FI signals. The same test was done using the range test tool for fixed coordinator as a local device with end device as remote.

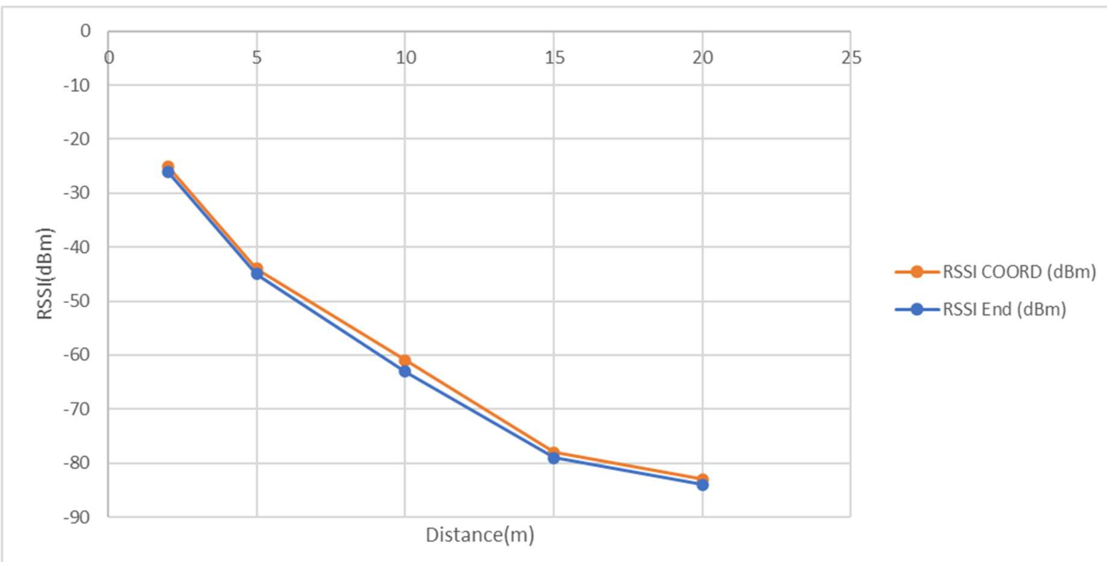

Figure 22 : Signal Strength with distance.

The signal strength was observed to be decreasing along with the increase in distance between the coordinator and end device. With the increase in distance there existed new obstacles such as wooden door after 5m, concrete wall after 10m which contributed in weakening of the signal. As shown on graph in figure 22 the signal strength were similar between the coordinator and end device. Various obstacles such as movement of people within the apartment, opening and closing of door were some of the reasons behind the decrease in signal strength.

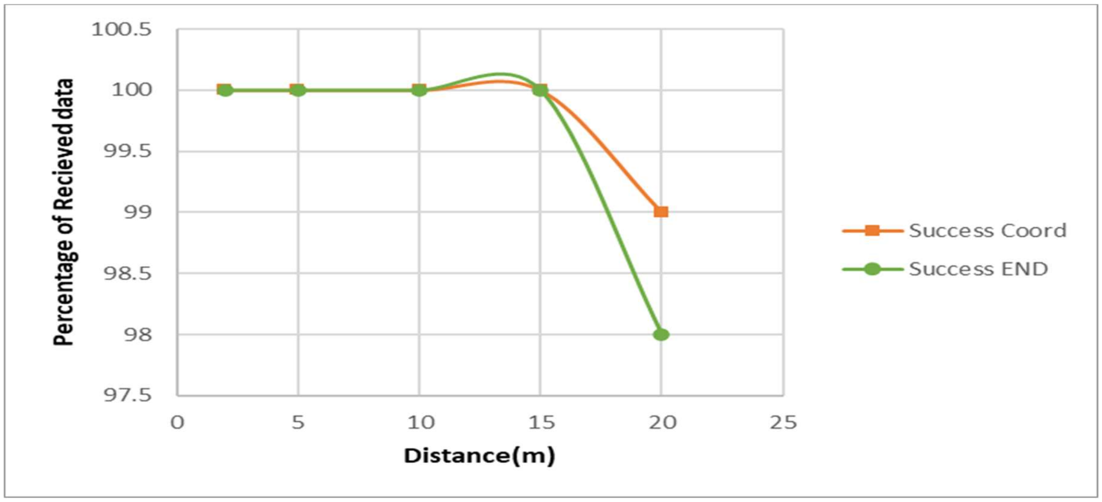

Figure 23: Percentage of received data with distance

The communication between two devices were found to be working despite some ocassional obstabcles as door and moving person blocking the signal.This resulted in packet loss as shown in graph on figure 23 which can be considered when setting up a sensor network indoor and positioning of the nodes can be crucial in obtaining the desired result.

6.1.2 Room to Corridor

This test was conducted between the room in first floor of the apartment to the corridor and two different floor with obstacle as a concrete wall, ladder and increase in height of almost 5m every floor between the fixed coordinator and end device.

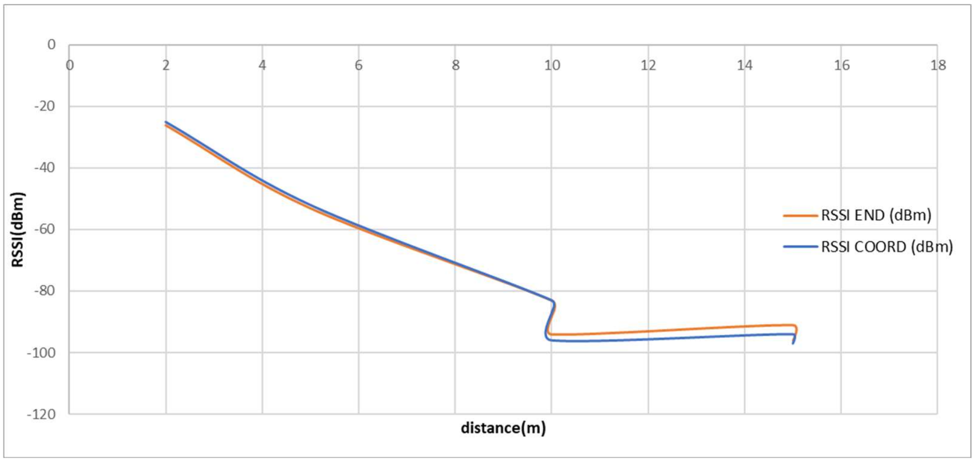

Figure 24: Signal Strength with distance and change in height.

The data obtained from the tests were mentioned in table 3 and table 4. As the test was conducted in different floor, the signal strength of network appears to be weak when both modules are placed in different height. This can be observed on graph in figure 24. The data were arranged in ascending order i.e. 2,5,10, and 15. The data included two different floors measurement together which presents sharp decrease in signal strength of the network although the distance between the modules are same. The obstacles such as a concrete wall, staircase and concrete ceilings played an important role in weakening the signal along the occasional movement of people across the hallway.

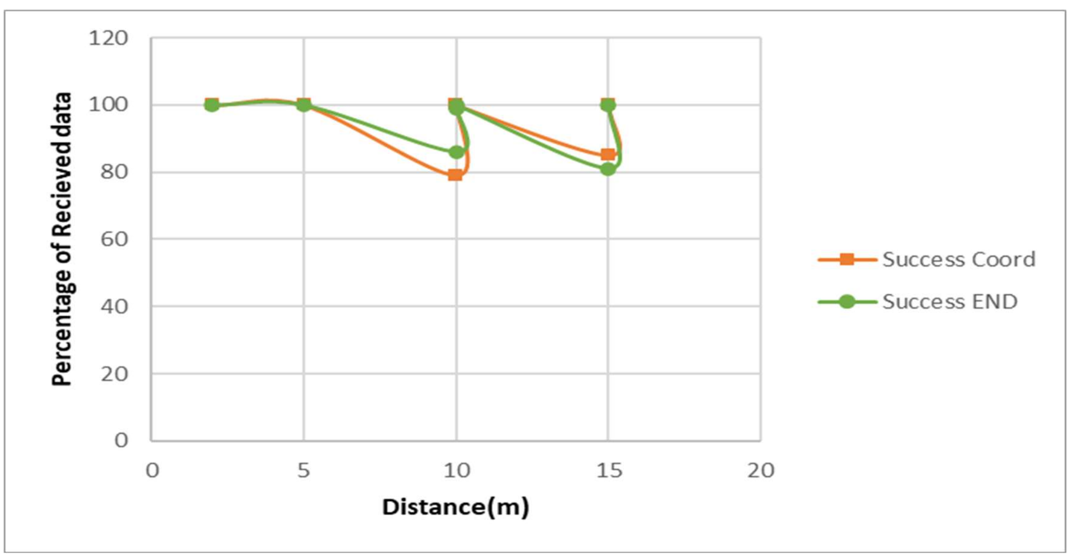

Figure 25: Percentage of received data with change in distance and floor.

The change in height between two modules resulted in packet loss which can be observed on the graph in figure 25. The sudden decrease in the percentage of received data at the same distance represents the measurement from two different floor i.e. at 10m distance range test was done in all three floors of the apartment and similar for 15m as well. The communication being unstable, resulted in multiple errors and lead to failure of the network.

6.2 Outdoor Tests

The outdoor tests were conducted in three different environments i.e. in a plain field, forest, and an urban environment. 50 packets of 50 bytes data were sent across both devices through the cluster ID 0x12 range test type in which received data is returned to the sender. The time window for the test was one minute with 1000ms Rx and Tx interval. Both local and remote RSSI in dBm was obtained through the range test along with the received packets and lost packets occurred in the communication. Table 5, 6, 9, 10, 13, and 14 from Appendix 2 contains the data obtained from the Indoor tests conducted using range test tool.

6.2.1 Plain Field

This test was conducted in Harustie street without the presence of any permanent physical obstacle and clear LOS between two modules. The test was done for a coordinator and end device by changing the distance between the coordinator and the end device. The range test tool was used to study the signal strength of the network.

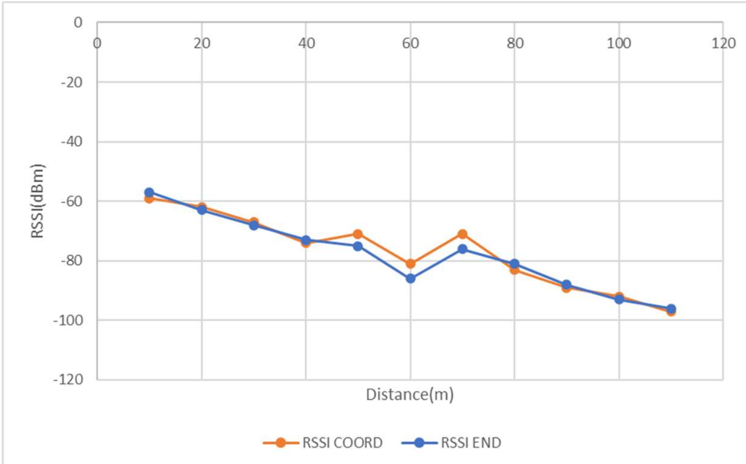

Figure 26: Signal strength of Coordinator and End device with distance

The signal strength in this test was found to be good enough for communication for a long distance as there was no physical obstacle present. The occasional movement of people acted as an obstacle and resulted in the weakening of the signal which can be observed in the graph shown in figure 26.

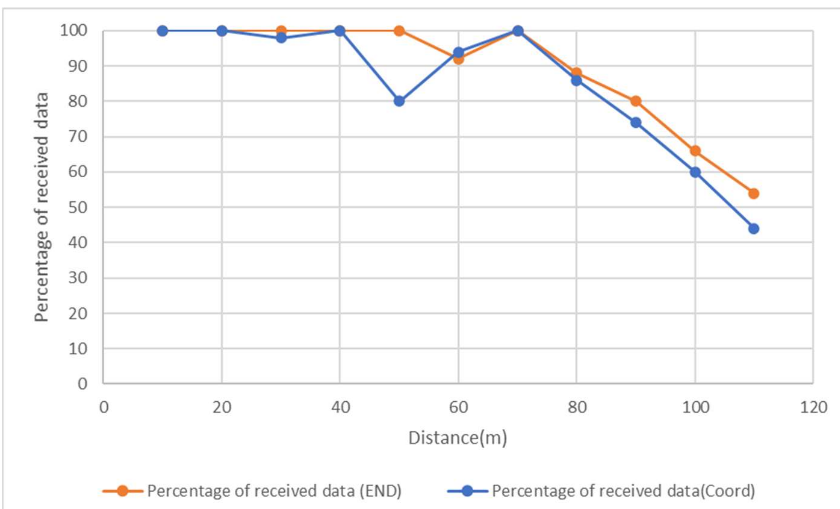

Figure 27: Percentage of received data with distance

Packets transmission was steady and error-free in the plain field. The temporary obstacles as people passing through the street resulted in the weakening of signal and caused error which can be observed in the graph on figure 27. After 80 meters the signal became weak and there started to occur error which resulted in communication error and lead to network failure.

6.2.2 Forest

This test was conducted in the forest nearby Meri-Rastila. In this test, different obstacles such as trees, bushes were present and LOS between the nodes were obstructed. The test was done using the range test tool for both coordinator and end device to study the signal strength.

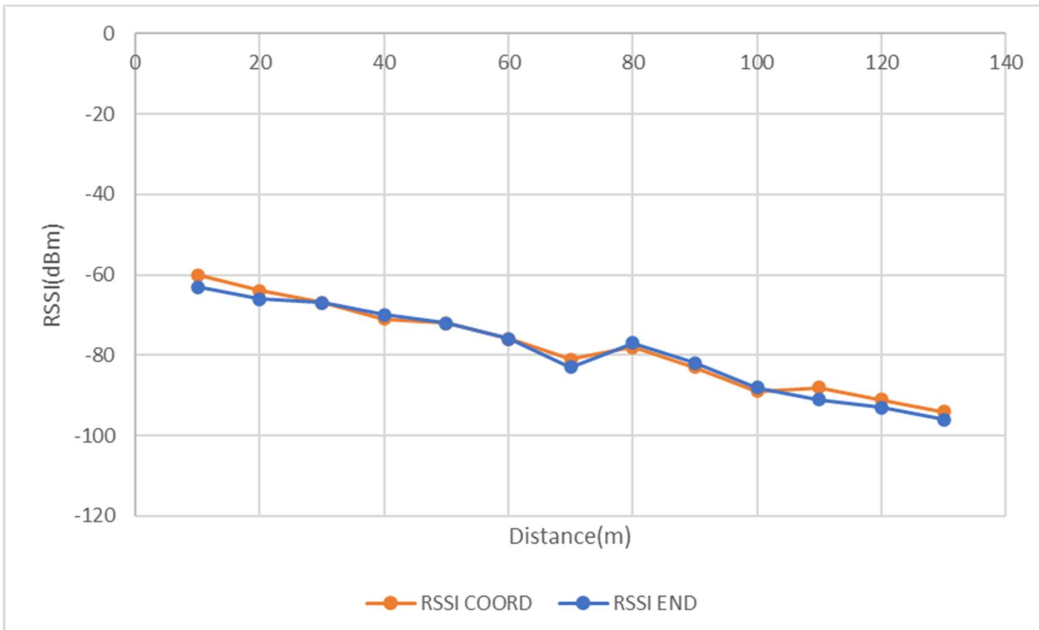

Figure 28: Signal strength with distance

With the increase in distance between the transmitter and the receiver and presence of obstacles as trees and bushes obstructing LOS, the network strength was decreasing as shown in graph on figure 28.

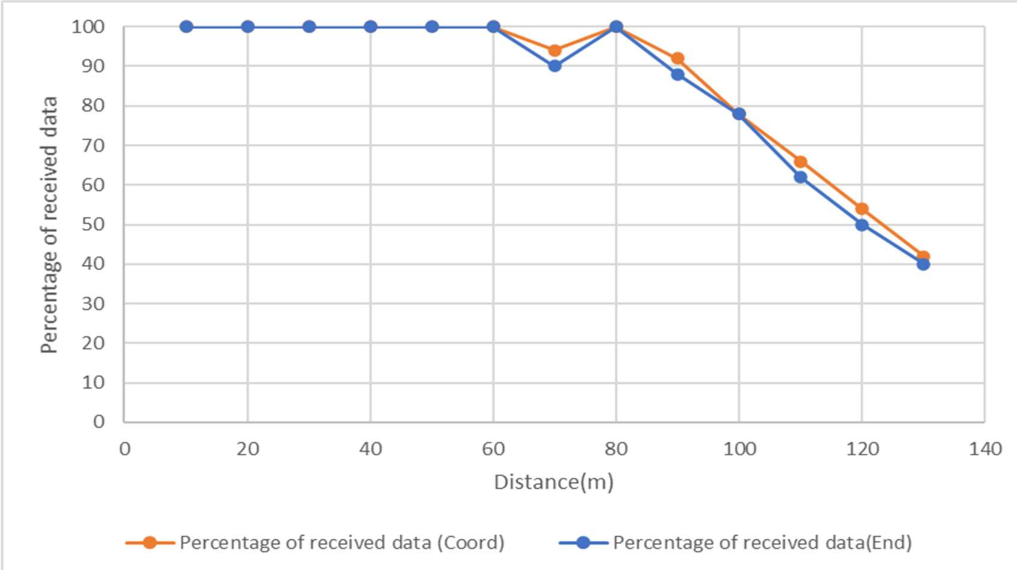

Figure 29: Percentage of received data with distance

The packets received at both transmitter and receiver were steady for a distance of 50m despite obstacle and started to slow down after that which can be observed on the graph in figure resulting in the increase in error and affecting communication between the transmitter and receiver.

6.2.3 Urban Environment

This test was conducted at a long corridor of the shopping center Columbus in Vuosaari. The test was done by placing a fixed coordinator with a change in distance of end device in the presence of obstacles as a cellular network, Wi-Fi, and people in the shopping center. The range test tool was used to study the signal strength of the network.

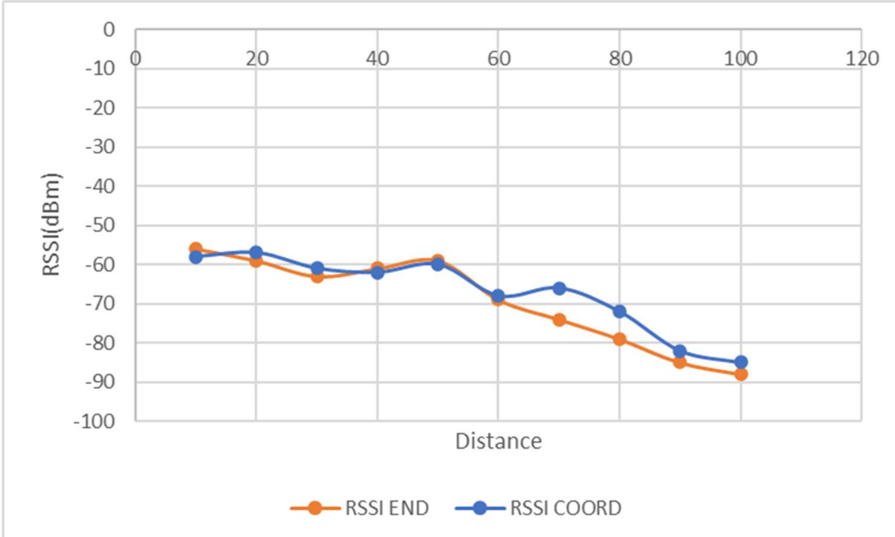

Figure 30: Signal strength with distance

The signal strength in the corridor was affected by the movement of persons inside the shopping center which can be observed in the graph from the figure 30. When the communication was free of the obstacle, the signal strength increased resulting in the restoration of the network.

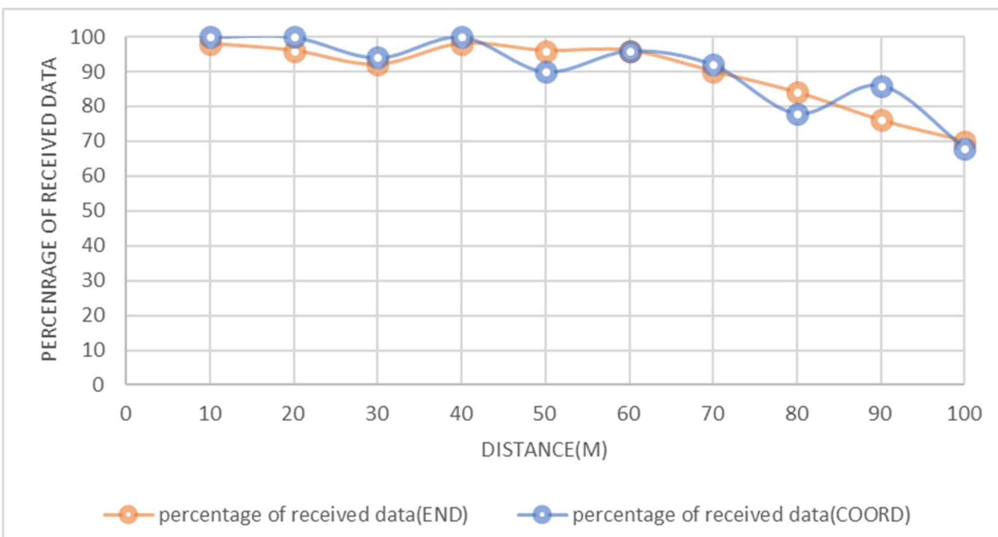

Figure 31: Percentage of received data with distance

The number of received packets reduced apparently as the people were walking across the corridor which caused obstacles in the first Fresnel zone which resulted in fading of the signal and loss of packets as shown in the graph on figure 31.

7 Analysis

In any wireless network, reliability of the network plays an important role. This depends on various parameters such as receiver sensitivity, transmitter output power, signal frequency, and the major factor which is the environment in which the network takes place. Digi mesh XBee3 used in the range test has a half wave dipole antenna of 2.4 GHz and unity gain of 2.1dBi with +8dBm as the transmit power. The signal power of the received packet at a distance d can be calculated from Friis Transmission equation in dBm [20]:

$$P_r = P_t + G_t + G_r - 20log_{10}R - 20log_{10}f + 20log_{10}\left(\frac{c}{4\pi}\right)$$

Where,

P_r = Power at the receiving antenna

P_t (Output power of transmitting antenna) = +8 dBm

G_t (Gain of transmitting antenna) = 2.1 dBi

G_r (Gain of receiving antenna) = 2.1 dBi

f (frequency of signal) = 2.4 GHz

c (Speed of light in vacuum) = $3x10^8$ m/s

R = distance between receiving and transmitting antenna.

Since, the values of P_t, G_r, G_t, c, and f are known and for given values of R, calculated values of power at the receiving antenna are shown in table 17.

Table 17: Signal strength of the network based on Friis Transmission equation (1)

Distance(m)	Power at the receiving antenna P_r(dBm)
10	-47.84
20	-53.86
30	-57.39
40	-59.88
50	-61.82
60	-63.41
70	-64.74
80	-65.90
90	-66.93

100	-67.84
110	-68.67
120	-69.43
130	-70.12

Table 17 presents the theoretical values of the power at the receiving antenna i.e. RSSI with the change in distance. The data is based on the given parameters and does not includes any obstacles, environmental conditions, and human obstacles.

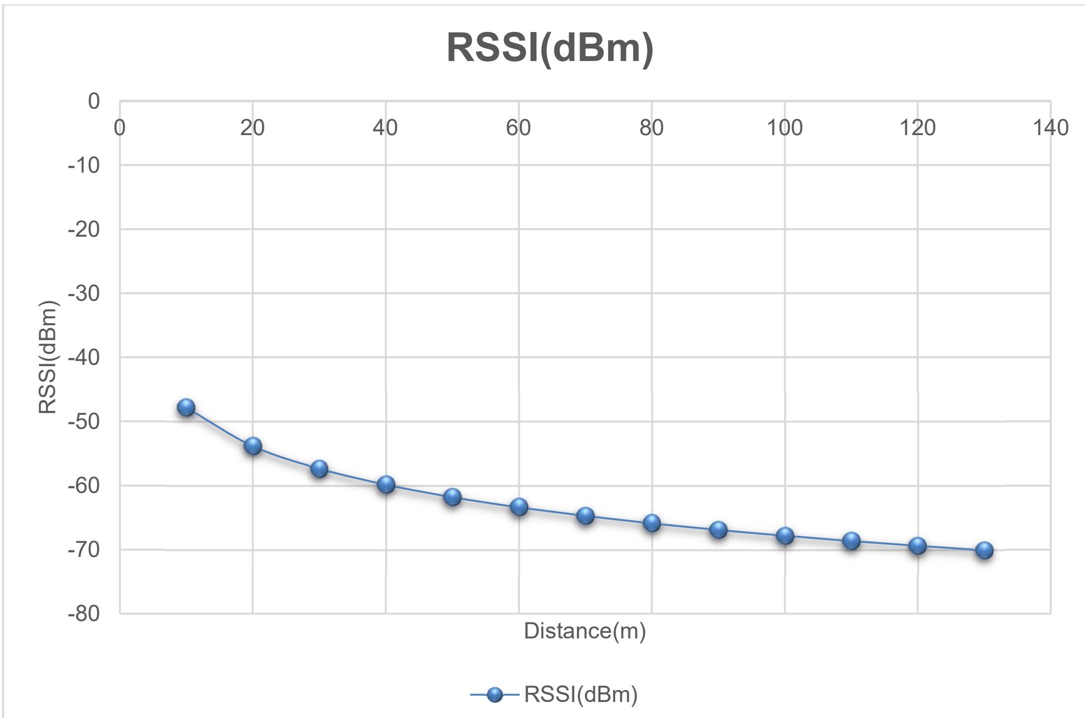

Figure 32: Signal strength with distance based on Friis Transmission Equation (1).

The RSSI of the receiving antenna gradually decreases with increase in the distance between the transmitter and the receiver as in figure 32. In practical application it is affected by the environment in which the network is established, presence of permanent obstacles, and the sudden obstacles blocking LOS.

In the indoor conditions there are various surrounding materials which absorbs the signal wave, some objects may reflect the signal while some absorbs the signal resulting in loss of data and weak signal in the receiver. The effect of signal penetration depends on the material that signal penetrates, materials like metal reflects almost all signal. During the indoor test, which was conducted between two rooms in an apartment and corridor of the building the signal strength was affected by the obstacles such as concrete wall and wooden door along with the occasional obstacles as people moving around there was occasional loss of packets and fading of signal as shown in figure 25.

In the outdoor conditions the test was conducted in three different environments: plain field, forest, and an urban environment. Among these three environments, the signal strength in forest was comparably good. The movement of peoples across the shopping center caused loss of signal and error in communication as the human body also attenuates the RF signal significantly because it consists about 70 percent of water and water in normal room temperature for 2.4GHz signal frequency has attenuation constant of 300dBm [8,174].

When a repeater (router) was added in the network the signal strength was good and the packets loss was reduced which helped in stability of the network and might be useful in extending the distance covered by the network. Table 7, 8, 11, 12, 15, and 16 from Appendix 2 contains the data obtained from Range test after adding router in the network.

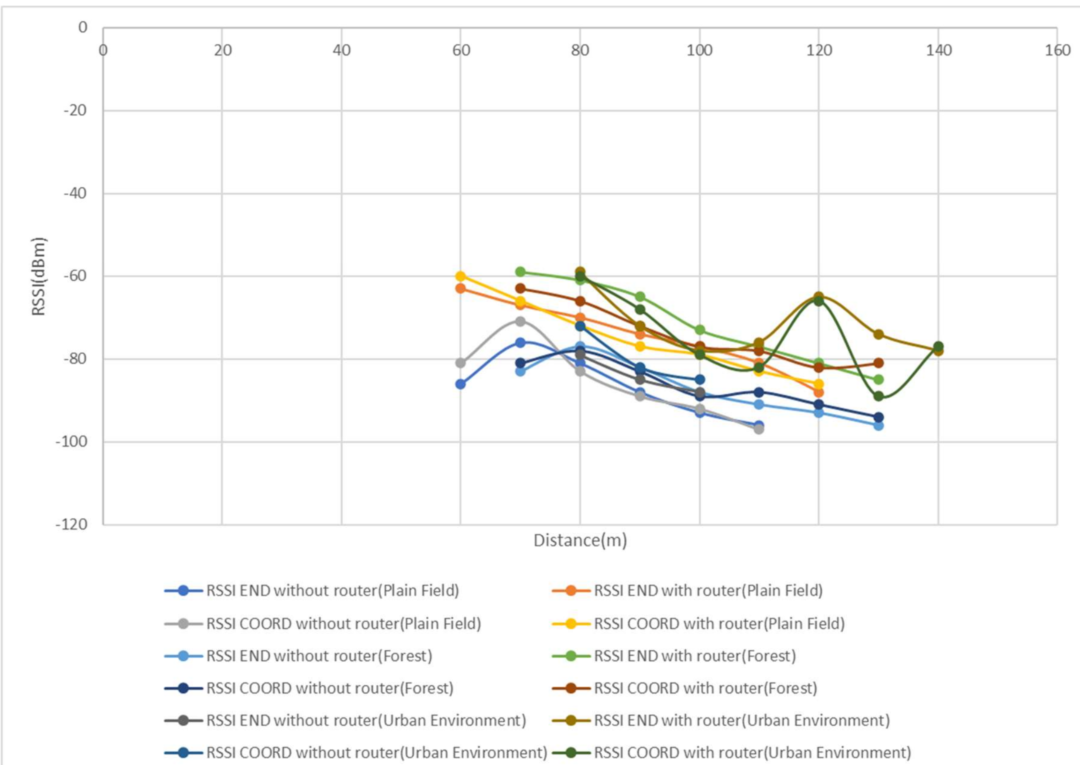

Figure 33: Signal strength with and without Router

With the addition of new device in the network at plain field(50m), forest(60m) and urban environment (70m) from the coordinator, the signal strength in the receiver increased in both the device as observed on graph in figure 33 and the range of the network is increased along with the stability.

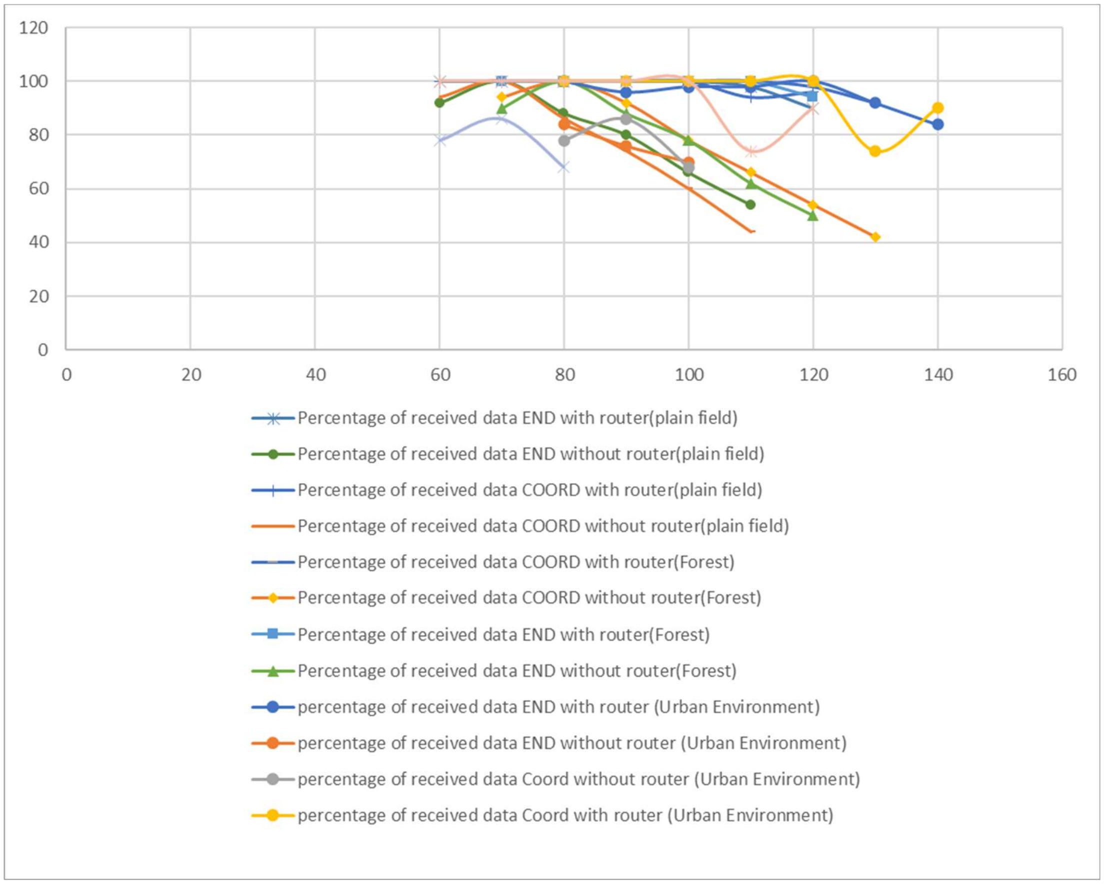

Figure 34: Percentage of received data with and without Router

The percentage of received data in both receivers improved along with the addition of router as shown on graph in figure 34.

8 Conclusion

The signal strength of ZigBee devices is affected by the environment in which they operate. So, to avoid the data loss the network should be free of obstacles and have a clear LOS. To establish a reliable network, the selection of the device for wireless sensor network needs to be done based on the environment of operation. Fresnel Zone should be taken into consideration when establishing a wireless sensor network as the signal reflected from obstacles can have a phase canceling effect. The selection and positioning of an antenna are an important factor in setting up the wireless network.

A physical survey of the site where the network is to be installed can be done to visualize the wireless network coverage, figure out possible obstacles and interferences. The signal strength of the receiver antenna from Range tests can be compared with theoretical calculations of the signal strength. Mesh networks can be done to prevent data loss and weakening of the signal as there will be multiple routes for the signal to travel.

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Indoor Test measurements:

Table 1: Range test data for End device (room to room)

SN	Time Interval(ms)	Packet received	Error	Percentage of received data	RSSI (dBm)	Distance (m)
1	1000	98	2	98	-84	20
2		100	0	100	-79	15
3		100	0	100	-63	10
4		100	0	100	-45	5
5		100	0	100	-26	2

Table 2: Range test data for Coordinator (room to room)

SN	Time Interval(ms)	Packet received	loss	Percentage of received data	RSSI (dBm)	Distance (m)
1	1000	99	1	99	-83	20
2		100	0	100	-78	15
3		100	0	100	-61	10
4		100	0	100	-44	5
5		100	0	100	-25	2

Table 3 : Range test data for End device(room to corriodor)

SN	Time Interval(ms)	Floor	Packet received	loss	Percentage of received data	RSSI (dBm)	Distance (m)
1	1000	3	86	14	86	-94	10
2		3	81	19	81	-96	15
3		2	100	0	100	-91	15
4		2	99	1	99	-88	10
5		1	100	0	100	-83	10
6		1	100	0	100	-53	5
7		1	100	0	100	-26	2

Table 4 : Range test data for Co-ordinator(room to corridor)

SN	Time Inter-val(ms)	Floor	Packet			RSSI (dBm)	Distance (m)
			received	loss	Percentage of received data		
1	1000	3	85	15	85	-97	15
2		3	79	21	79	-96	10
3		2	100	0	100	-94	15
4		2	100	0	100	-87	10
5		1	100	0	100	-83	10
6		1	100	0	100	-52	5
7		1	100	0	100	-25	2

Outdoor Test Measurements

Table 5: Range test data for End Device (Plain Field)

SN	Packet received	Packet loss	Percentage of received data	RSSI (dBM)	Distance(m)
1	50	0	100	-57	10
2	50	0	100	-63	20
3	50	0	100	-68	30
4	50	0	100	-73	40
5	50	0	100	-75	50
6	46	4	92	-86	60
7	50	0	100	-76	70
8	44	6	88	-81	80
9	40	10	80	-88	90
10	33	17	66	-93	100
11	27	23	54	-96	110

Table 6: Range test data for Coordinator (Plain Field)

SN	Packet received	Packet loss	Percentage of received data	RSSI (dBm)	Dis-tance(m)
1	50	0	100	-59	10
2	50	0	100	-62	20
3	49	1	98	-67	30
4	50	0	100	-74	40
5	40	10	80	-71	50
6	47	3	94	-81	60
7	50	0	100	-71	70
8	43	7	86	-83	80
9	37	13	74	-89	90
10	30	20	60	-92	100
11	22	28	44	-97	110

Table 7: Range test data for End Device (Plain Field) with router at 50m

SN	packet re-ceived	Packet loss	Percent-age of received data	RSSI (dBm)	Dis-tance (m)
1	50	0	100	-63	60
2	50	0	100	-67	70
3	50	0	100	-70	80
4	50	0	100	-74	90
5	50	0	100	-77	100
6	49	1	98	-81	110
7	45	5	90	-88	120

Table 8: Range test data for Coordinator (Plain Field) with router at 50m

SN	packet received	Packet loss	Percentage of received data	RSSI (dBm)	Distance (m)
1	50	0	100	-60	60
2	50	0	100	-66	70
3	50	0	100	-72	80
4	50	0	100	-77	90
5	50	0	100	-79	100
6	48	2	96	-83	110
7	47	3	94	-86	120

Table 9: Range test data for End Device (Forest)

SN	re-ceived packets	Packet loss	Percentage of received data	RSSI (dBm)	Dis-tance (m)
1	50	0	100	-63	10
2	50	0	100	-66	20
3	50	0	100	-67	30
4	50	0	100	-70	40
5	50	0	100	-72	50
6	50	0	100	-76	60
7	45	5	90	-83	70
8	50	0	100	-77	80
9	44	6	88	-82	90
10	39	11	78	-88	100
11	31	19	62	-91	110
12	25	25	50	-93	120
13	20	30	40	-96	130

Table 10: Range test data for Coordinator (Forest)

SN	re-ceived packets	Packet loss	Percentage of received data	RSSI (dBm)	Dis-tance(m)
1	50	0	100	-60	10
2	50	0	100	-64	20
3	50	0	100	-67	30
4	50	0	100	-71	40
5	50	0	100	-72	50
6	50	0	100	-76	60
7	47	3	94	-81	70
8	50	0	100	-78	80
9	46	4	92	-83	90
10	39	11	78	-89	100
11	33	17	66	-88	110
12	27	23	54	-91	120
13	21	29	42	-94	130

Table 11: Range test data for End Device (Forest) with router at 60m

SN	Received Packet	Packet loss	Percentage of received data	RSSI (dBm)	Distance (m)
1	50	0	100	-63	70
2	50	0	100	-66	80
3	50	0	100	-72	90
4	50	0	100	-77	100
5	50	0	100	-78	110
6	49	1	98	-82	120
7	46	4	92	-81	130

Table 12: Range test data for Coordinator (Forest) with router at 60m

SN	Re-ceived Packet	Packet loss	Percentage of received data	RSSI (dBm)	Distance (m)
1	50	0	100	-59	70
2	50	0	100	-61	80
3	50	0	100	-65	90
4	50	0	100	-73	100
5	50	0	100	-77	110
6	47	3	94	-81	120
7	45	5	90	-85	130

Table 13: Range test data for End device (Urban Environment)

SN	Received Packet	Packet loss	percentage of received data	RSSI (dBm)	Distance (m)
1	49	1	98	-56	10
2	48	2	96	-59	20
3	46	4	92	-63	30
4	49	1	98	-61	40
5	48	2	96	-59	50
6	48	2	96	-69	60
7	45	5	90	-74	70
8	42	8	84	-79	80
9	38	12	76	-85	90
10	35	15	70	-88	100

Table 14: Range test data for Coordinator (Urban Environment)

SN	Received Packet	Packet loss	percentage of received data	RSSI (dBm)	Distance (m)
1	50	0	100	-58	10
2	50	0	100	-57	20
3	47	3	94	-61	30
4	50	0	100	-62	40
5	45	5	90	-60	50
6	48	2	96	-68	60
7	46	4	92	-66	70
8	39	11	78	-72	80
9	43	7	86	-82	90
10	34	16	68	-85	100

Table 15: Range test data for End device (Urban Environment) with router at 70m

SN	Received Packet	Packet loss	percentage of received data	RSSI (dBm)	Distance (m)
1	50	0	100	-59	80
2	48	2	96	-72	90
3	49	1	98	-78	100
4	49	1	98	-76	110
5	50	0	100	-65	120
6	46	4	92	-74	130
7	42	8	84	-78	140

Table 16: Range test data for Coordinator (Urban Environment) with router at 70m

SN	Received Packet	Packet loss	percentage of received data	RSSI (dBm)	Distance (m)
1	50	0	100	-60	80
2	50	0	100	-68	90
3	50	0	100	-79	100
4	50	0	100	-82	110
5	50	0	100	-66	120
6	37	13	74	-89	130
7	45	5	90	-77	140